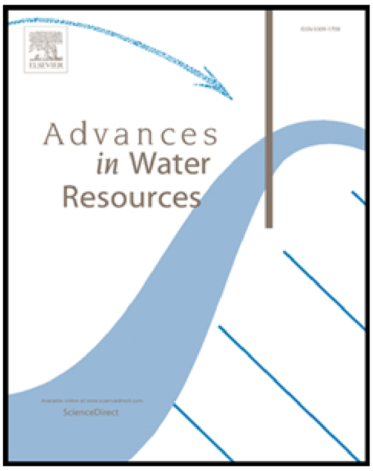

Derivation of canonical total-sequences triggering landslides and floodings in complex terrain

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Highlights

- stablishing Austrias most comprehensive database of weather-triggered hazards
- Creation of an ‘event space’ (1950-2015) comprising more than 20000 hazards
- Objective derivation of hazard-inducing weather sequences (climate indices)
- Characteristic linkage between weather sequences, process categories and regions
- Demonstration of general applicability across a wide topographical range
- Contribution to public protection through improving early warning strategies

Derivation of canonical total-sequences triggering landslides and floodings in complex terrain

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Abstract

Floodings and landslides are amongst the most devastating damage-processes worldwide. Associated risk levels are particularly high in topographically complex terrain. Along with the increase in climate-change induced extreme-events, research devoted to the identification of so-called Climate Indices (CIs) describing weather phenomena triggering hazard-occurrences and intensities gain rising emphasis.

In this study we accomplish the first-time unification of the three most comprehensive cadastres on weather-induced hazard-processes, compiled and maintained by federal authorities. The therefrom resulting 'event space' stretches seven decades from 1950 onwards and contains more than 20.000 hazard occurrences, classified into different process-categories. Event data are analyzed together with a high-quality, daily-based dataset providing tem-

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peratures and precipitation totals on a 1 km grid across the Austrian part of the European Alps.

On the resulting unprecedented extent of extreme-weather triggered hazard-processes and gridded weather observations we are able to examine the hypothesis that daily sequences of precipitation-totals preceding damage-events allow for detecting temporal weather sequences uniquely allocatable to various hazard-categories in three orographically distinct regions in the European Alps. We pursue this research aim by analyzing for each hazard-category its quadratic form representing the physics contained in the observations. Resulting eigen-directions, invariant under its inherent second order tensor, are the sought-for total-sequences (CIs) and hence reject the alternative hypothesis. Therefore, precipitation total-sequences can be uniquely assigned to hazard categories within each region.

It is important to note that findings based on this novel, objective approach do not contradict, but rather add to attained research achievements by introducing this new perspective on the subject.

Obtained CIs have substantial potential in research and applications. In civil defense, safeguarding critical infrastructure, early warning systems and the development of sustainable protection strategies, findings are in implementation by responsible decision-makers and in intense discussion with the European Freight and Logistics Leaders' Forum.

Keywords:
precipitation-totals, weather-sequences, hazard-processes, objectively determined climate indices, event space, Austria

1. Introduction

Extreme weather induced hazards have always been substantial threats and will, in the wake of climate change, pose major challenges to societies particularly in complex terrain. Having remained constant on high levels for about a decade, global mean temperatures are again on the rise since some years by now. Unlike global temperatures that increased about 1 degree Celsius over the past 150 years, those in European Alps rose twice as much (Auer et al., 2007). Natural hazards-processes accompanying this rapid change present significant challenges to those responsible for civil protection. Albeit averages are important, the focus of this paper is on changes in extreme events, as their impact on society, ecosystems and socio-economic structures is far more significant (Katz & Brown, 1992; Schlögl & Laaha, 2017).

This endeavor is challenging, because extreme events are rare and, hence, data should be of high spatial-temporal density and quality as well as stretch many decades back in time. Temporal extent is of outstanding importance because three decades e.g. are already required for determining climate (mean, variance - i.e. lowest moments, WMO, 2017). Hence, describing rare events far off the averages requires substantially more observations. Unfortunately, both prerequisites – to be concerned in case of weather observations as well as hazard-occurrences (meaning when- and wherever hazards occur, weather observations should be on hand) – are nearly ever met. Therefore it is important to establish a solid data basis allowing for further development as it was carried out e.g. in Portugal (Pereira et al., 2018) and Italy. Guzzetti et al. (1994, 2007, 2008), e.g. searched the technical and scientific literature to establish a first and further developed catalog containing rainfall events (mostly in Italy) that partly resulted in landslides. On that basis the authors compiled a collection of information on rainfall-induced landslides in Italy comprising 753 precipitation events causing landslides. Concerning landslides Brunetti et al. (2010) managed to add detailed or rough location as well as time or period of occurrence. Regarding associated precipitation events the authors provided information on averaged intensity and duration, too. By using two statistical methods and various further subsidiary information (e.g. class within the Köppen scheme, main rock types). They were able to identify thresholds indicating potential precipitation caused landslides for a region in central Italy and Italy as a whole. Melillo et al. (2015) pointed out inconsistencies corresponding to rainfall reconstruction methods used and proposed a procedure estimating precipitation conditions potentially triggering landslides in an objective and reproducible way. Therefore they utilized 229 landslide observations and rain gauge data in Sicily between 2002 and 2012. Based on these studies, Peruccacci et al. (2017) investigated (mainly shallow) landslides and defined new precipitation thresholds for Italy and 26 regions. Mostbauer et al. (2018) analysed the temporally varying roles of rainfall, snowmelt and soil moisture on debris flow initiation by combining a rainfall–runoff model with with documented debris flow events. In a recent effort, Prenner et al. (2019) investigated trigger characteristics of torrential flows in alpine regions based on 360 observed debris flow and fluvial flood events. These studies show that despite the lack of actual observation (making it appear almost impossible to establish precipitation – landslide relationships), exploitation of subsidiary information (e.g. topography, Köppen classes), rainfall reconstructions and known sum-intensity relations can be used to derive rainfall thresholds indicating degrees of landslide-risk important for public protection. All this research serves a good example for the success of continued efforts.

In the current study, however, we approach the subject from the different perspective: Focusing on landslides and floodings, we examine the hypothesis whether it is possible to derive characteristic, local-scale precipitation total-sequences for various hazard-processes prior threat-occurrences in different regions in the European Alps.

From an orographical and climatological point of view, Austria can be separated into three distinct provinces. Northern parts extending from the foothills of the Alpine ridge across the River Danube northwards (henceforth summarized as: 'Northern Lowlands', NL) are geomorphologically characterized by lowlands interspersed by flat hills. Geologically, NL can be further separated into the Bohemian Mass in its North, mainly consisting of granite and migmatite, and its South, dominated by classic sediments (gravel, sand, clay) of the Molasse zone. Climatologically, NL is generally influenced by northern and north-western air-flows.

The southeastern basins ('Southern Basin Chain', SB) comprising, for instance, the Styrian Basin and the Klagenfurt Basins, are defined by flat topography and low-altitude mountains. SB mainly consists of classic sediments, partly of mica slate and volcanic rocks. Weather conditions are mainly controlled by air-masses advected from the south and southeast, as well as occasionally by Vb pattern induced through Genua-cyclogenesis.

The remaining area, summarized here as 'Alpine Territory' (AT), is signified by large differences in elevation, ranging from low altitude basins of only somewhat more than hundred metres above mean sea level and deep valleys to high mountains of over 3500 m. Aside from its geomorphologcal appearance, it is marked by diversity in terms of geology as well. AT exhibits different types of rocks, represented by Flysch Zone and Limestone Alps northwards and a mixture of volcanites as well as various slate and gneiss groups in its southern parts. The Alpine crest acts as a meteorological divide, whereby Northern and Central Alps form a barrier for northwestern airflows. Therefore mean annual precipitation totals reach more than 3000 mm. Inner alpine valleys such as the Inntal,the Ötztal and the Mölltal are shielded by their surroundings and therefore particularly dry (Matulla, 2005; Schwarb et al., 2001).

Our research is devoted to crucial subject areas in public protection and safeguarding critical infrastructure against damaging events caused by weather-driven threats. We aim at supporting decision-makers as well as European Freight and Logistic Industries establishing sustainable adaption strategies, thus fostering society's ability to cope with future risk potentials. This is pursued by objectively determine CIs, applying findings to downscaled future climate-change projections forced by different pathways of mankind (RCPs, van Vuuren et al., 2011) and the using decision-theory for decisions under risk.

In meteorology, extreme events are often defined as states exceeding high percentiles of atmospheric quantities. In case hazards, damages, fatalities and public protection are concerned, extreme events are associated with atmospheric pattern jeopardizing citizens, ecosystems and infrastructure assets. Descriptions related to the latter are called Climate Indices – CIs.(see e.g.

Schlögl & Matulla, 2018; Matulla et al., 2017a).

Across Europe's complex structured alpine terrain, floodings, landslides, heat and drought bear the largest share of losses, totaling up to one billion Euro per year in Austria alone (Steininger et al., 2016). Therefore, changes in threat-intensities and -frequencies are a subject of growing concern. Consequently, gaining knowledge on weather-processes triggering hazards (i.e. deriving CIs) is the key for establishing successful and sustainable protection strategies. For every hazard-triggering process described by a CI, pertaining future evolutions can be derived from downscaled climate change projections corresponding to different pathways of mankind. Once these future spatial-temporal CI-appearances (in terms of occurrence frequency and intensity) are on hand, they are the cornerstone for developing sustainable protection programs suitably adapted to each pathway.

CIs are of outstanding importance for their central role in studies on natural hazards,too, whose validity directly depends on the quality of utilized CIs. The more accurately CIs represent hazard-inducing processes, the more reliable results obtained with them are. We deduce CIs from meteorological observations pertaining in space and time to hazard- occurrences on record. This approach has not been explored yet for its high demand on observations. Generally, datasets on extreme events are short, unchecked and of small extent and, thus, under circumstances to date this approach would have been unsuitable. However, the composition of our consortium consisting of federal officials responsible for public protection (i.e. decision-makers), climate researches from the weather service and young researchers from universities enabled the first-time unification of Austria's three most comprehensive cadastres on hazards and the utilization of high-quality datasets. This setup permitted the establishment of an 'event space' providing an unprecedented scope of threat occurrences enabling the derivation of CIs from observations.

The present paper is dedicated to the objective determination of CIs related to several hazard-categories of landslides and floodings in topographically distinct regions stretching across Austria's complex territory. Section 2 'Data and Methods' presents the three, in terms of spatial-temporal extent and the amount of hazard-observations on record, most comprehensive Austrian cadastres as well as the meteorological data-base utilized. Besides that, we present a concise review of the methods just serves to recall their analysis-techniques applied here. Section 3 'Results and Discussion' briefly describes the creation of 'event space' and discusses the identified canonical total-sequences triggering different hazard-categories in three distinct regions. The paper is closed by an outlook given in section 4.

2. Data and Methods

2.1. Data

Data used in this study are of two kind. On one hand there are long-term records of damage-processes collected by federal agencies in compliance with their legal mandate. Most other poolings of such kind developed much later when damages induced by extreme-weather increasingly raised public attention and political awareness in the early 2000s. On the other hand we have high-quality, daily weather observations processed on grids provided by the Austrian national weather service.

Below presented governmental cadastres follow grown labels oriented to the agencies' obligations but chosen in such way that they can be grouped into internationally common categories. However, since the number of pertaining observations is of outstanding significance allowing to objectively identify extreme-weather processes driving hazards to the public, we will start therefrom.

The *Austrian Service for Torrent and Avalanche Control* ('Wildbach- und Lawinenverbauung', 'WLV'), founded in 1884, is a subordinate agency of the Austrian Federal Ministry of Sustainability and Tourism (BMNT). WLV traditionally deals with torrents and avalanches, which mainly occur within the Alpine Territory (AT, see Fig. 1). Amongst WLV's tasks are: declaration of danger zones potentially yielding settlement-prohibitions, civil protection management and providing advisory capacity towards climate-change adaption. These (and many more) responsibilities require diligently collected, long-term records of hazard-processes that are compiled in the 'WLV-cadastre' (WLV, 2017). It covers *fluvial sediment transport* processes (see Tab. 1), which are floods containing amounts of solids up to one fifth their volume (3603 events on record); *debris-flow-like processes* – as before, but with a fraction of solid material exceeding one fifth (766); *mud flows*, carrying solid contents exceeding 50% (1927); *flooding* (1976); and *surface water* (16).

Landslides are distinguished into *rotational slides*, which are movements exhibiting a rotation about an axis parallel the slopes (202); *translational slides*, i.e. slides with negligible rotation (100); *earth- and debris-flows*, where the material sliding down is subjected to strong deformation (319); *shallow landslides* (162); *individual blocks* with block sizes up to 1 meter (58); *large*

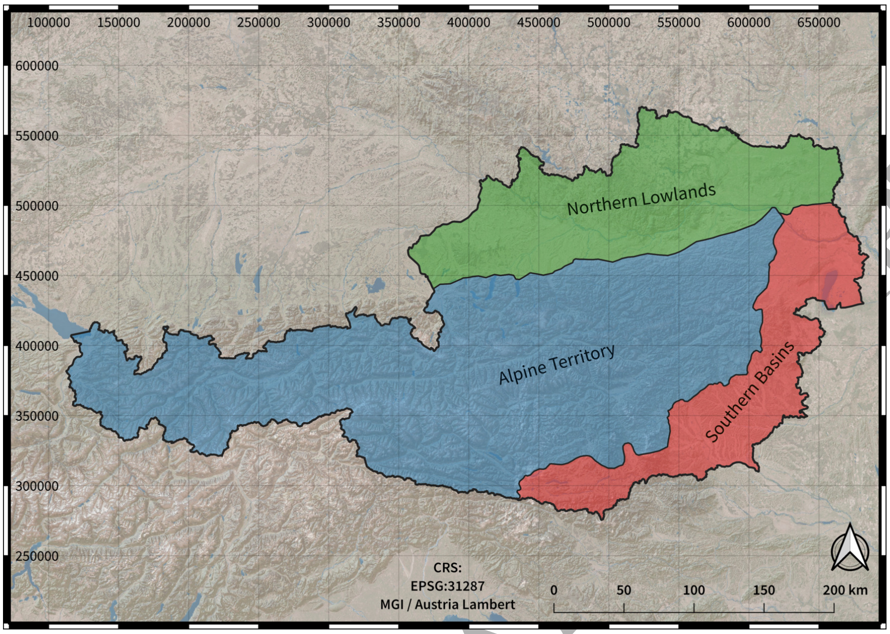

Figure 1: Austrian parts of the European Alps and and the three regions employed in this study.

blocks with sizes exceeding one meter (239); as well as *rock creeps* (2).

Founded in 1849, the *Geological Survey of Austria* ('Geologische Bundesanstalt', 'GBA') is a subordinate agency of Austrian Federal Ministry for Education, Science and Research (BMBWF). Fields of activity encompass geological mapping, process-monitoring and issuing of maps featuring high-risk areas for planning purposes, whereby emphasis is on the foothills of the Alps, on lowlands (Northern Lowlands, NL) and basins / Southern Basin Chain, SB, see Fig. 1). Just as in case of WLV, the accomplishment of GBA's governmental obligations requires a highly dependable, comprehensive, and statistically robust data basis. Such sound, conscientiously collected, long-term records of damage-events are compiled in the 'GBA-cadastre' (Geologische

Bundesanstalt, 2017). Therefore various observation systems are employed. Amongst these are, for example, remote-sensing, field surveys, geographical photographs, systematic expert-inventories of indexed areas, reports from the population, digitizing historical archives (from e.g. monasteries). To avoid inhomogeneities, which may result from different formats, quality criteria and degrees of information content, GBA devotes a substantial fraction of its resources to maintaining an extensive quality assurance program to ensuring just that. GBA-records used in this study start in 1950 and cover (see Tab. 1) the following gravitational processes: *slides* (2201), *flows* (104), *falls* (898), *general mass movement* (52), *mass movement in loose rock* (28), and *complex large-scale movement* (37).

The *Austrian National Weather and Geophysical Service* ('Zentralanstalt für Meteorologie und Geodynamik','ZAMG') was founded in 1851 and is a subordinate agency of BMBWF. Its legal duties cover the operation of the meteorological observation network, the warning of citizens in case of hazardous weather, supporting disaster management and advancing current states of knowledge in the realm of meteorology and climate through independently carried out research. Amongst its various weather datasets, ZAMG maintains since 1948 an archive of media reports on weather-driven damage-processes according to given procedures. 'VIOLA' (VIolent Weather Assessment) (Matulla et al., 2017b) contains a digitized version of this archive, organized in line with legal duties. It's group-definitions are trans-nationally compatible and allow by simple aggregation conformity with internationally used categories. Here we use *continuous rain* (337), *heavy precipitation events* (2351), *thunderstorms* (2290), *surface water* (1761), *slides* (665), *flows* (656), *falls* (180), and *heat and drought* (528).

Weather data are taken from **SPARTACUS**, the ‘Spatiotemporal Reanalysis Dataset for Climate in Austria’ (Hiebl & Frei, 2015, 2017). It provides high-quality, daily temperatures and precipitation totals from 1961 onwards on a 1 km grid across Austria. SPARTACUS has been generated in an international collaboration from irregularly distributed weather stations maintained by ZAMG, has already found application in several studies (Duethmann & Blöschl, 2018; Schroeer & Kirchengast, 2018) and is operationally kept up-to-date at ZAMG. Precipitation totals throughout the decade prior SPARTACUS (from 1951 to 1960) are taken from the so-called GPARD6 dataset (Hofstätter et al., 2015), which provides daily totals at a less highly resolved grid of 6 km spacing.

Table 1: Overview of process types and number of events by data source. The period covered from each data source is 1950 until 2017. Please note that hazard-processes are written in lower case.

Source	**processes**	$\mathbf{n_{events}}$
WLV	individual block (Einzelblock)	58
	large block (Blockverband)	239
	fluvial sediment transport (Fluviatiler Feststofftransport)	3603
	debris-flow-like process (Murartiger Feststofftransport)	766
	flood (Hochwasser)	1976
	surface water (Oberflächenwasser)	16
	shallow landslide (Hangmure)	162
	mud flow (Murgang)	1927
	earth- and debris flow (Erd- Schuttstrom)	31
	rotational slide (Rotationsrutschung)	202
	translational slide (Translationsrutschung)	100
	rock creep (Talzuschub)	2
	landslide (not differentiated) (Rutschung nicht differenziert)	427
GBA	slide (Gleiten/Rutschen)	2201
	flow (Fließen)	104
	falling / toppling (Fallen/Stürzen)	898
	complex large-scale mass movement (Komplexe Großmassenbewegungen)	37
	mass movements (in loose rock) (Massenbewegung im LG)	28
	mass movements (general) (Massenbewegungen (allg.))	52
VIOLA	continuous rainfall (Dauerregen)	337
	heavy rainfall (Starkregen)	2351
	thunderstorm (Gewitter)	2290
	surface water (Oberflächenwasser)	1761
	slide (Gleiten/Rutschen)	665
	flow (Fließen)	656
	falling / toppling (Fallen/Stürzen)	180
	heat & drought (Hitze & Dürre)	528

2.2. Methods

Descriptions of weather phenomena triggering hazard-processes are, as mentioned already, called 'Climate Indices' (CIs). CIs are of mulitfarious use: they indicate hazardous weather and thereby help alert inhabitants of affected areas; they serve as benchmarks for climate-proof construction work; and they permit the assessment of future vulnerability of e.g. infrastructure, settlements and traffic routes under climate-change (Matulla et al., 2017a; Schlögl & Matulla, 2018).

Precipitation periods of five or more days, for instance, with overall-totals larger than 137.3 mm and least one daily sum above 25.6 mm, have been defined by Guzzetti et al. (2008) as a CI for landslides in the European Alps.

So far CIs are based on expert opinion, practical experience, physical reasoning (e.g. various threshold models), experiments and model considerations, but CIs have not been objectively derived from records by now. This is for two reasons: (i) detailed knowledge on hazard-events and triggering weather conditions have to be on hand (let's call that kind of observation: 'hazard-weather' observation); (ii) many decades of 'hazard-weather' observations are required. Please note, having a large number of these 'hazard-weather' observations available is not sufficient unless these stretch many decades. This is because (as already elaborated) already three decades are required for deriving the lowest moments of meteorological elements' distributions. Thus, much more time is needed to properly assess extremes, far off the means (e.g. Alexandersson et al., 2000; Bärring & von Storch, 2004; Matulla et al., 2008a).

Generally, detailed information on neither hazard-occurrences nor triggering weather conditions are available. And its only due to substantial efforts that – by reviewing scientific literature, blogs, reports by fire fighters, etc. on one hand as well as continued research endeavours in terms of e.gẇeather reconstructions on the other hand - catalouges on damage-occurrences and knowledge on related weather conditions are usable for proposing CIs (Guzzetti et al., 1994, 2007; Brunetti et al., 2010; Gariano et al., 2015).

In the following we set out to investigate whether our 'event space' and SPARTACUS allow for the objective determination extreme-weather sequences triggering damage-processes (i.e. objectively derived CIs). On top of that we claim that it is possible to objectively identify definite sequences of daily weather observations that are distinguishable amongst various categories of floodings and landslides as well as in-between the three above introduced regions.

Please note that this statement is extraordinary. We do not only set out to (i) objectively identify CIs regarding floodings and landslides, which has not been done yet. We aim at doing so for (ii) various landslide- and flooding-categories and we claim them to (iii) exhibit characteristic sequences of daily precipitation totals, which are (iv) distinguishable amongst hazard categories as well as (v) in-between regions.

This is in fact by no means likely or expectable, because the 'event space' generated here is based on cadastres assembled by different authorities and SPARTACUS results from an international collaboration. Hence, the data available to us are from various, independent sources. Everybody who had worked already with datasets from different sources, knows how large differences can be, even if they describe the same e.g. weather element. Here, SPARTACUS is a meteorological dataset and the 'event space' contains hazard-occurrences and now they linked at different points in time and space – whenever these is a damage-occurrence. Apart from that, the assumption (iii) concerning particular successions is not suggested by anything. CIs derived in other studies contain conditions that may or may not be matched. Landslides in the European Alps, for instance, are triggered by weather phenomena exceeding two threshold in whatever order (see above). So, there is no need for any order and hence claims (iv) and (v) are obviously even less reasonable.

As such, let us claim there is no detectable difference between successions of daily precipitation totals inducing different flooding- and landslide-processes within and in-between the alpine regions considered.

Since date and location of each event space element is known, we assign to it corresponding precipitation totals at its occurrence day (or target-day, 'TD') as well as during the preceding week. Concerning continental Europe, this complies with a rather common rule of thumb, resulting from studies reaching back into the 1930s. Baur (1936) and singled out periods of 5-8 days adequately characterizing changes in predominant weather conditions. Cadez (1957) observed weather developments over five years in Slovenia and found three-day periods to predominate. Hess & Brezowsky (1969) investigated a range of large-scale weather patterns from 1881 to 1998. They confirmed three-day cycles as well as periods extending from five to seven days to carry much significance. Ehrendorfer (1987) identifies 3 to 7 days signifying duration and change of large-scale weather characteristics over Central Europe.

Since we are not only interested in currently dominating weather, but also in conditions preceding their arrival, periods of 8 days are considered here. The considered 8-day sequence-length covers the mean climate weather's retention time and well enough the threat-process' development history (e.g. Matulla et al., 2008b). In our analyses we regard for every hazard-occurrence 8-day total-sequences averaged over the closest SPARTACUS grid-point and its four neighbors. That means, we have 'hazard-weather' observations (see above) over seven decades available. For all event space elements of one category (N events), we set up a $8 \times N$ matrix O of observations. The central question now arising is: 'Are there characteristic patterns to the sequences towards target day or are the totals arbitrarily distributed?'. The answer depends on the symmetric tensor OO' (i.e. O times O-transpose), since its eigen-directions (resulting from the secular equation) are the sought total-sequences (CIs). Hence, we can address the above hypothesis by analysing and depicting them (see Figs. 2 – 7).

The theory of second order symmetric tensors is identical to those of quadratic forms (Duschek & Hochrainer, 1946), which in physics generally represent energy expressions, e.g. potential and kinetic energy in mechanics; deformation-work in statics; magnetic and electric energy in electrotechnology (Zurmühl, 1950). The second order, symmetric tensor OO' and its mathematically-inherent form contains all weather observations (in terms of total-sequences) preceeding considered hazard-events ('hazard-weather' observations) and thereby all physics recorded at this linkage.

Now form, tensor and eigen-directions are canonically linked: on one hand eigen-directions are invariant under tensor operations and on the other hand, taken as basis they display form and tensor in their main axis and diagonal representation. The eigen-directions are in our context the canonical total-sequences.

It is worth noting that the canonical total-sequences shown in Figs. 2–7 result from an analysis in meteorology and several other applied fields called Empirical Orthogonal Function Analysis (EOF, e.g. von Storch & Zwiers (1999)) a multivariate statistical analysis tool of great use in applications, especially when dealing with incomplete, inaccurate data.

Amongst the most prominent EOF applications is perhaps that of successively observed surface level air-pressure 'SLP' across the North Atlantic and Europe. There the analysis yields pattern 'EOFs', which together with their 'temporal coefficients' (aka PCs, e.g. Preisendorfer et al., 1988) represent the atmosphere's dynamic (North Atlantic Oszillation, Trenberth & Paolino, 1981). The first EOF of SLP over the Northern Hemisphere, the 'Arctic Oscillation' and its dynamics is perhaps even better known (Kutzbach, 1970; Hurrell, 1995).

With an EOF analysis one achieves two important goals at once: (i) the physics observed through EOFs and their time-coefficients (PCs) as well as (ii) avoidance of erroneous information by disregarding small eigenvalues (EVs). For these features the EOF analysis is popular. Both of them result from the EOFs' orthogonality.

In textbooks EOFs are usually introduced by explicit construction, because it only requires very basic skills in mathematics that way (e.g. Peixoto & Oort, 1992; von Storch & Navarra, 1999; Zorita & von Storch, 1999). That is perfectly all right, but makes some readers believe EOFs' orthogonality, which is used in this construction is arbitrary. And *that* is wrong. In fact, the pattern's orthogonality is mathematically inherent since OO' is a symmetric, second order tensor (identical theory to euclidean geometry, which we obviously use to observe, to measure objects) (Duschek & Hochrainer, 1950; Duschek, 1963).

3. Results and Discussion

3.1. Compilation of the 'event space'

In this section we follow the steps carried out towards the compilation of the 'event space' and shortly point out its main features that are on the one hand inherited from the authorities' cadastres (introduced above) and generated on the other hand by means of their aggregation. Amongst the significant features taken over from the cadastres three stand out: the period covered (i.e. about seven decades from 1950 onwards); the regions and their spatial extent that are to be supervised by the authorities for their legal obligations and the equivalence of the hazards-processes to be monitored to acquire their targets.

Ultimately, it is the combination of these traits allowing all results presented here. And these, in turn, are of importance for decision-makers realizing sustainable civil-protection strategies geared to climate driven challenges induced by changing hazard- frequencies and intensities throughout the decades to come until 2100.

All findings achieved here depend on their comprehensive content extending over seven decades.These results could not have been derived from data that only began in the 2000s when climate-change was already known and altered extreme-events became popular. These data are too short.

The technical challenges of compiling the 'event space' have not been any different than they are in general – known to all involved in the merging of information from different sources (data formats, arrangement of information, etc.). The only general lesson is the indispensability of patience, continuous inquiring, accuracy and dedication.

However, it is worth mentioning that the classification ('processes' in Tab. 1) used by the authorities to accomplish their legal tasks have been introduced thoughtfully such that they split internationally common categories (c.f. Heiser et al., 2015) or allow for their straightforward assignment to these. Hence, there was no complication to be experienced in this regard. Tab. 2 shows internationally common categories and how pertaining events are distributed over the above introduced orographical distinct provinces (Fig. 1). *Floodings*, to begin with, are made up by WLV's *fluviatile sediment transport*, *debris-flow like transport*, *floods* and VIOLA's *continuous rain.Flash floods* combines VIOLA's *surface water*, *heavy precipitation events* and *thunderstorms* with WLV's *surface water*. *Slides* aggregates WLV's sub-categories *rotational slides* and *translational slides* as well as GBA's and VIOLA's correspondences (i.e. *slides*). *Flows* contains GBA's and VIOLA's equivalents (i.e. *flows*) as well as WLV's *mud flows*, *shallow landslides* and *earth- and debris-flows* reflecting just a further distinction. *Falls* consists of GBA's and VIOLA's *falls* as well as WLV's *individual blocks* and *large blocks*, while finally category *Others* acts as a reservoir for sparsely occupied and undifferentiated processes.

The above described integration of the three most extensive national damage-process databases (WLV, GBA, VIOLA), which is accomplished here for the first time results in an ‘event space’ made up of internationally used categories (e.g. Varnes, 1978; Hungr et al., 2001, 2013). This ‘event space’ provides an unprecedented scope of hazard-processes (i.e. about 20.000 occurrences) in terms of *Floodings*, *Flash Floods*, *Slides*, *Flows* and *Falls*, covering a significant part of the European Alps. The captured outstanding extent of events does not only allow for the examination of weather-sequences driving floodings and landslides, but to do so in their various appearances mentioned above as well as in the three regions (see Fig. 1).

3.2. Derivation of CIs

Throughout the past seven decades several thousand hazard events have been recorded within each region and every category. Based on this statistically robust set up, we investigate temporal total-sequences extending over eight days (including the ‘target-day’) preceding hazard occurrences.

Figures 2 through 7 below refer to *Floodings*, *Slides* and *Flash Floods* for different regions. These are presented in a standardized layout: their upper rows depict (from left to right) (1) share of variances explained, displayed in a ‘scree-plot’ (Compagnucci & Salles, 1997; Horn, 1965), (2) the fraction of hazard-occurrences recorded in this region and finally (3) the distribution of totals accumulating over the 8-day sequences. The figures’ bottom line illustrates (from left to right) the three leading EOFs’ temporal pattern (i.e. the canonical transformation’s temporal total-sequences triggering damage-processes). The color of the Figures’ frames correspond to the region investigated, as can be seen in Figure 1.

Note that the scree plot refers to the fraction of physics (contained in

Table 2: Overview of processes contained in the categories *Flash Floods* (6311 events), *Floodings* (6241), *Slides* (3006), *Flows* (2600), *Falls* (1223) and *Others* (625) and their distribution across the Alpine Territory, the Northern Lowlands and the Southern Basin Chain. Please note that the Categories are capitalized.

Category	processes	region
Floodings	floods (WLV), fluvial sediment transport (WLV), debris-flow-like processes (WLV), continuous rain (VIOLA)	AT: 78 % NL: 11 % SB: 11 %
Flash Flood	surface water(WLV & VIOLA), heavy precipitation events (VIOLA), thunderstorms (VIOLA)	AT: 47 % NL: 29 % SB: 24 %
Slides	slides (GBA & VIOLA), rotational slides (WLV), translational slides (WLV)	AT: 65 % NL: 13 % SB: 22 %
Flows	flows (GBA & VIOLA), shallow landslides (WLV), earth- and debris flows (WLV), mudflows (WLV)	AT: 93 % NL: 3 % SB: 4 %
Falls	falls (GBA & VIOLA), individual blocks (WLV), large blocks (WLV)	AT: 79 % NL: 10 % SB: 11 %
Others	landslides (not differentiated) (WLV), complex large-scale mass movements (GBA), mass movements (in lose rock) (GBA), mass movement (general) (GBA), rock creep (WLV)	AT: 65 % NL: 15 % SB: 20 %

all observed precipitation processes) represented by their EOF-pattern. A gap between the values corresponding to EOFs of increasing number or a change in the course indicates the appropriate number of EOFs to retain in the subsequent analyses. While there are in fact a number of criteria for deciding the number of EOFs used to capture the signal from the rest containing noise, we decided by scree-plots to retain three EOFs in each shown case.

The results for *Floodings* in the Northern Lowlands (666 events, Fig. 2) and in the Alpine Territory (4884 events, Fig. 3) display a clearly visible difference between the most frequently attained sequence-total (fist row, rightmost panel) between the alpine topography and the northern plains. While this value reaches 30 mm in NL, the corresponding amount in AT is 25 mm. This seem to match with expectations related to the regions' distinct orography and thus pertaining catchment area sizes.

Concerning the explained variances of the leading EOFs, there is no significant difference between the regions (40 % and 42 %). However, the patterns themselves differ obviously. *Floodings* in NL are triggered by sequences exhibiting a steep increase in daily totals from TD-2 until process-occurrence. In contrast, AT's leading precipitation totals are starting a continuous rise from TD-4 until TD-1 followed by a slight decrease at the target day. The course of the second leading patterns – 23 % and 31 % for the corresponding explained variances, respectively – somehow reverses that of the first and come with clearly larger daily sums from the sequences' beginning up to TD-3. The explained variances (14 % and 10 %) pertaining to the third canonical total-sequences, triggering *Floodings*, make up already only a quarter of those

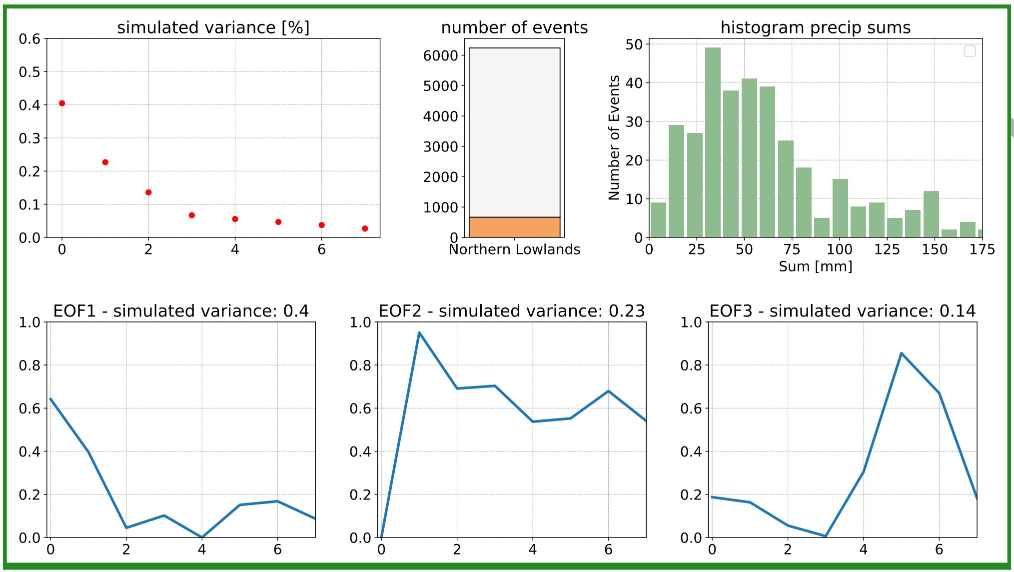

Figure 2: Triggering precipitation characteristics of *Floodings* in the Northern Lowlands.*

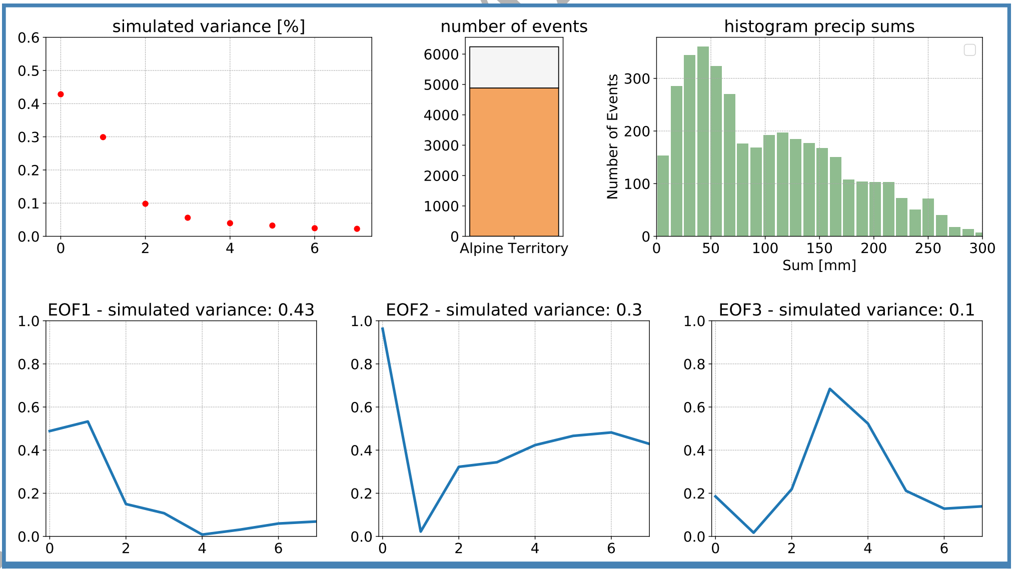

Figure 3: Triggering precipitation characteristics of *Floodings* in the Alpine Territory.*

* Note: Please find a comprehensive explanation detailing the content of all panels in the text.

associated with the first and, hence, carry accordingly less importance. However, unlike above discussed EOFs, their runs highlight the first half of the sequences towards TD, whereby NL's has its maximum sum on TD-5 and AT's on TD-3. This may be related to rather different sizes of the regions' catchment areas. The captured behavior of *Floodings* in the Southern Basin Chain (SB, not shown) is much alike with the one obtained for NL.

Figures 4 and 7 depict findings for *Slides* in the Southern Basin Chain (392 events) and across the Alpine Territory (1706 events). Slides generally happen in open terrain and tear-off particularly along edges like those brought by forest roads, favoring infiltration processes.

The explained variances of the leading sequences are rather different, showing values of 34 % and 58 %. Their courses of daily sums, on the other hand, share some similarities in terms of overall appearances. These are: reaching their maximum sums at TD-1 and generally rising totals towards them as well as decline afterwards. This indicates a one-day time-lag between weather-development and the thereby initiated hazard-process, that is related to the soil moisture. This phenomenon is sometimes referred to as a 'delayed reaction', as opposed to an instantly triggered slide directly caused by high rainfall intensity.

Second EOFs exhibit explained variances of 18 % and 21 % in SB and AT, respectively. Developments of totals are in both cases different from those just mentioned. Here, precipitation sums take on their minima one and two days prior the event in SB and AT, while both attain their maxima at TD itself – i.e. 'instant trigger' in experts' terms. The difference between 'instant' and 'delayed' hazard initiation may arise from geological conditions as well

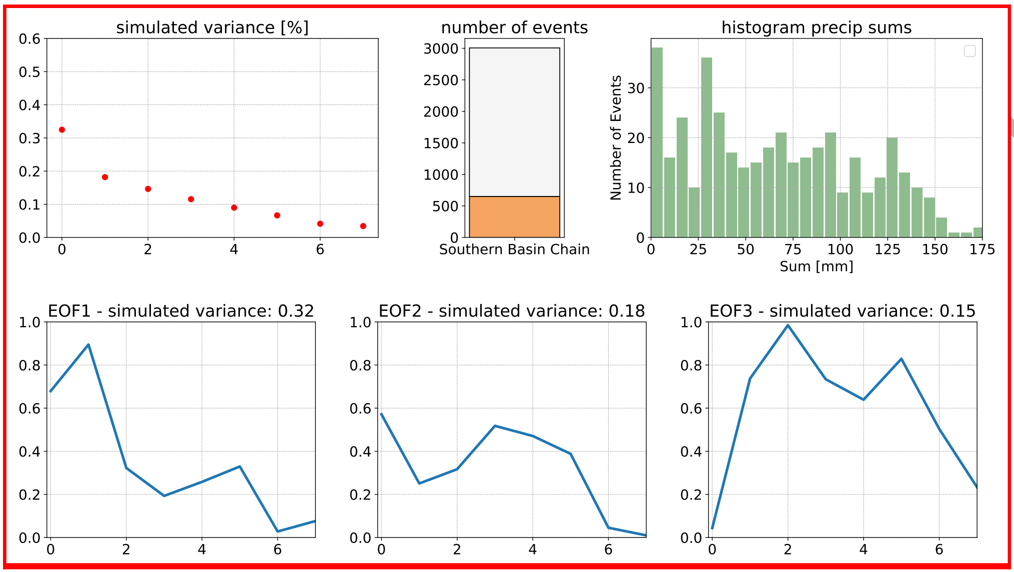

Figure 4: Triggering precipitation characteristics of slides in the Southern Basin Chain.*

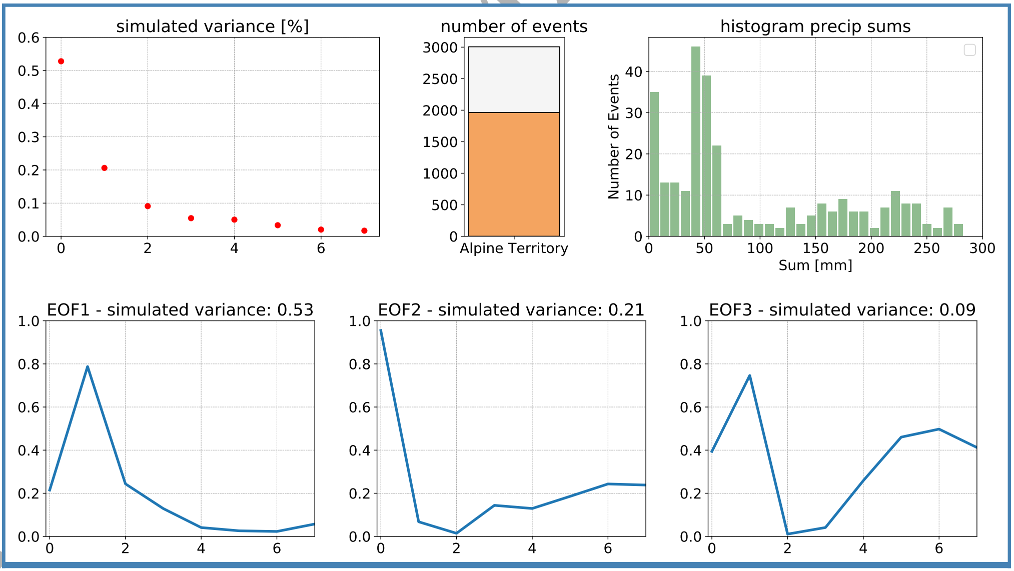

Figure 5: Triggering precipitation characteristics of slides in the Alpine Territory.*

* Note: Please find a comprehensive explanation detailing the content of all panels in the text.

as differences in the water saturation of the soil. In this context 'instant' and 'delayed' slides ought to be anticipated with Flysch and calcareous substrate.

Large totals reached from TD-3 backwards may highlight the importance of infiltration and saturation processes, acting as prerequisites of slides. This characteristic also stands out in case of the third patterns, featuring explained variances of 13 % and 9 %, respectively. Sufficient moisture-penetration slowly propagates towards sliding layers in all sliding processes. Generally, slides occur delayed when penetration has reached so-called 'critical depths', which depend on the actual slide-mightiness.

Total-sequences in the Northern Lowlands share obvious similarity with those of SB just mentioned.

Figures 6 and 7 refer to results of category *Flash Floods* within the Northern Lowlands (1816 events) and the Alpine Territory (2297 events). The first patterns, having sudden and pronounced maxima on TD, mirror the definition of *Flash Floods* (Merz & Blöschl; Nied et al., 2014). In NL, however, the explained variance is considerably larger than that of AT (40 % versus 56 %).

Second EOFs (22 % for NL and 13 % in AT) again reverse the temporal order of minimum and maximum totals compared to the leading sequences. Apart from that, AT's pattern attains the largest daily sum on TD-1 whereas in NL on TD-2. This was already the case for *Floodings* such as the fact that they come with larger daily sums until TD-1. Unlike in all other cases shown, third total-sequences show reflected behaviour in-between the regions. Sums in NL show an overall increase up to TD-1 whereas AT's pattern features rather large totals from the beginning until TD-2, followed by its minimum

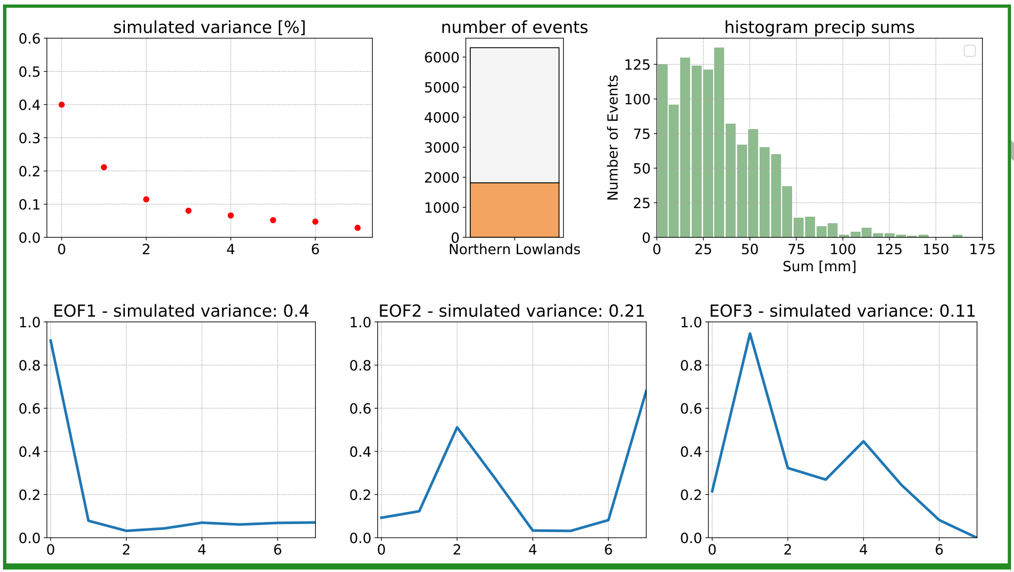

Figure 6: Triggering precipitation characteristics of flash floods in the Northern Lowlands.*

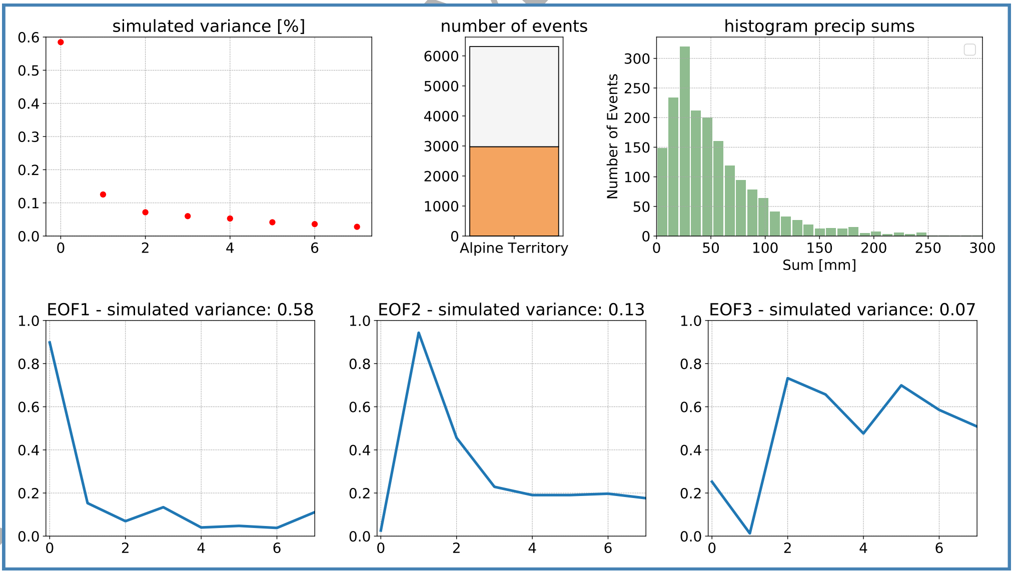

Figure 7: Triggering precipitation characteristics of flash floods in the Alpine Territory.*

* Note: Please find a comprehensive explanation detailing the content of all panels in the text.

and somewhat more precipitation on TD. The relative gap between the explained variances stays approximately the same as that before. Results for *Flash Flood* in the Southern Basin Chain show close resemblance to those in the Alpine Territory.

The main statement of the whole study standing out from all examinations and analyses is the significance and uniqueness of total-sequences tied to each single hazard-category-region pairing (totaling up to 18 CIs: three regions with four and two categories for landslides and floodings, respectively).

As such our hypothesis, related to the question whether it is possible or not to derive characteristic total-sequences (CIs) for various hazard-categories prior threat-occurrence, may therefore be decided. The claim there is no detectable difference between successions of daily total-sequences either inducing the same hazard (floodings and landslides in various categories) in topographically distinct regions or triggering different hazards within the same region, has to be rejected.

So, the 'event space' generated and the eigen-directions of our quadratic form comprising the physics through all observations, allow to objectively determine canonical CIs (total-sequences) triggering damage-processes.

The validity of the region-specific CIs despite their inner variability (due to their geological, physiographical and geomorphological conditions, land-cover and soil types etc.) reveals its subsidiary status. The validity of the hazard-sensitive CIs in-between regions and on the other hand illustrates their statistical robustness.

It is perhaps worth mentioning that none of our findings here contradict or render obsolete already established CIs. The current outcomes only add to the research achievements of those, for instance, discussed throughout this paper as well as (Caine, 1980; Martelloni et al., 2012), who managed to continuously improve landslide threshold levels in various regions across Italy by enlarging the body of rainfall-landslides information and enhancing analysis-techniques. These endeavors are highly relevant in terms of public protection for instance, because landslides perpetrate substantial economic losses and high numbers of fatalities. In terms of floodings, which are addressed here too, the accurate estimation of extreme-precipitation totals and the proper simulation of their effects are decisively contributing to civil protection as well (Scofield & Kuligowski, 2003; Papaioannou et al., 2018).

Results derived in this study are to be used by responsible decision-makers for the purpose of public protection as well as safeguarding critical infrastructure. Together with ensembles of downscaled climate change projections driven by different pathways of mankind, they serve as cornerstone for sustainable strategies assembling bundles of protection measures (that are to be effective, modularly extendable, combinable with structures already in effect and cheap to maintain). Aside from their importance for establishing sustainable protection strategies, they are subject to close collaboration with European Freight and Logistics Leaders Forum's members in order to secure their business.

4. Outlook

Future work will focus on the application of CIs to empirically-statistically as well as dynamically downscaled ensembles of climate change projections driven by various pathways of mankind. This shall enable decision-makers in charge to develop sustainable strategies for e.g. public protection and safeguarding critical infrastructure geared to future climate conditions expected throughout the decades to come. Other goals worth to attain refer to case studies focusing on subsidiary effects, to differentiate between seasons and to investigate whether the actual extent of landslides reveal geomorphological fingerprints and can be allocated to rapid or delayed initiation. Aside from these aims we set out together with those in charge integrating findings into early warning systems as CIs derived in this study exhibit daily resolution, stretch a period of 8 days and are characteristic for combinations of hazard-process and region (AT, NL, SB). Thus, operationally observed weather developments, may be continuously compared to CIs without any additional effort. In case evolutions match them after e.g. 5 days enhanced alertness and appropriate preparation protocols may be brought into effect. Such precautions can buy time when time is most critical.

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